IEP UB RAS
Russian Academy of Sciences
Institute of Electrophysics
Pulsed Power Laboratory

HIGH CURRENT AND CURRENT RISE RATE THYRISTOR BASED SWITCHES

A. Gusev, S. Lyubutin, A. Ponomarev, S. Rukin,

B. Slovikovsky, S. Tsyranov

CERN ARIES FCC hh ee he

PULse POwer for Kicker Systems (PULPOKS) workshop 2018

Outline

IEP UB RAS

1. Introduction

2. SOS generators

3. Thyristor switches operated in impact-ionization wave mode

    3.1 Effect of dU/dt and Temperature on Switching Process

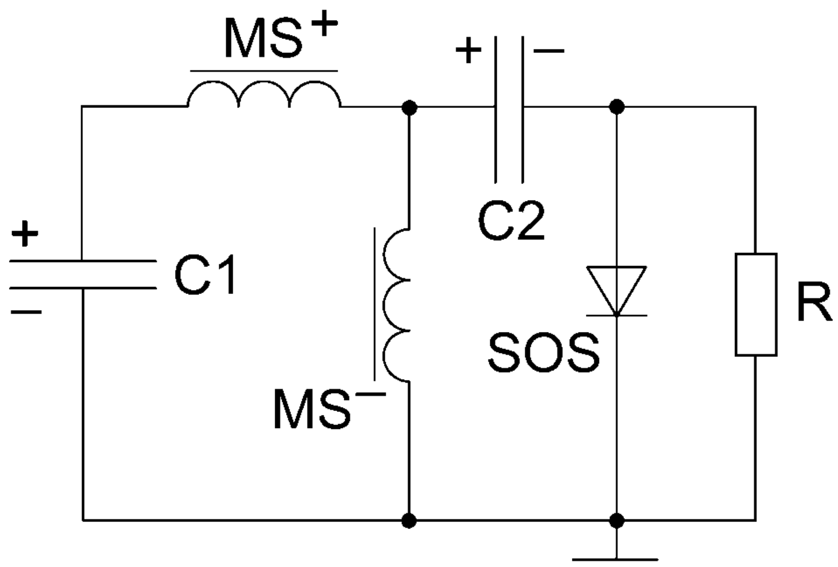
    3.2 Repetitive Mode of Operation

4. Conclusion and Future Works

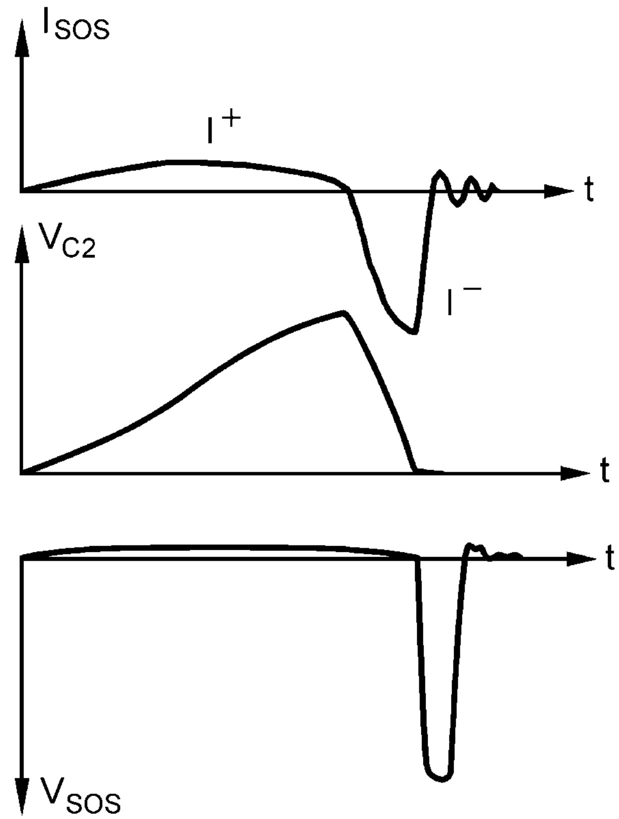
About Pulsed Power Laboratory

IEP UB RAS

Semiconductor Opening Switches (SOS) based on SOS effect - discovered in Institute of Electrophysics, Ekaterinburg, Russia in 1992



Simplified electric circuit diagram of the generators based on Semiconductor Opening Switch (SOS).



Qualitative diagrams of the currents and voltages in the circuit.

Desktop SOS generators

IEP UB RAS

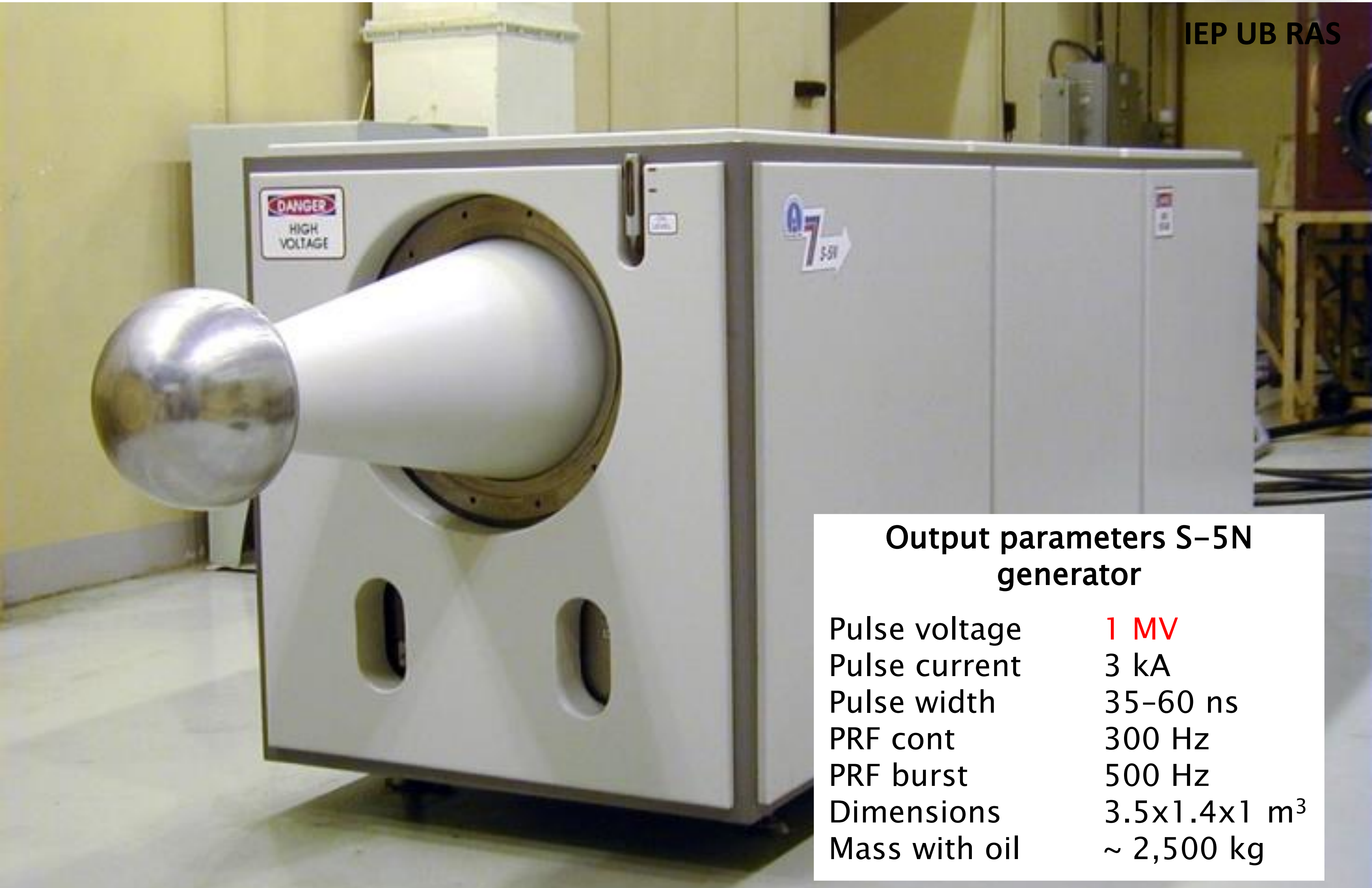
SM-2N

SM-3NS

Parameter	SM-2N	SM-2NS	SM-3N	SM-3NS
Output peak voltage	100-200 kV	120-220 kV	150-400 kV	200-400 kV
Pulse current	0.2-0.4 kA	0.3-0.8 kA	1-2 kA	1-3 kA
Peak power	30-50 MW	60-100 MW	300-500 MW	400-600 MW
Pulse duration (FWHM)	25-40 ns	3-6 ns	20-50 ns	5-8 ns
Continuous PRF	1 kHz	0.4 kHz	0.3 kHz	0.3 kHz
Burst PRF	5 kHz	3 kHz	2 kHz	3 kHz
Case length	0.62 m	0.62 m	1.2 m	1.4 m
Mass with oil	~50 kg	~60 kg	~250 kg	~300 kg

SOS generators of GW-range

IEP UB RAS

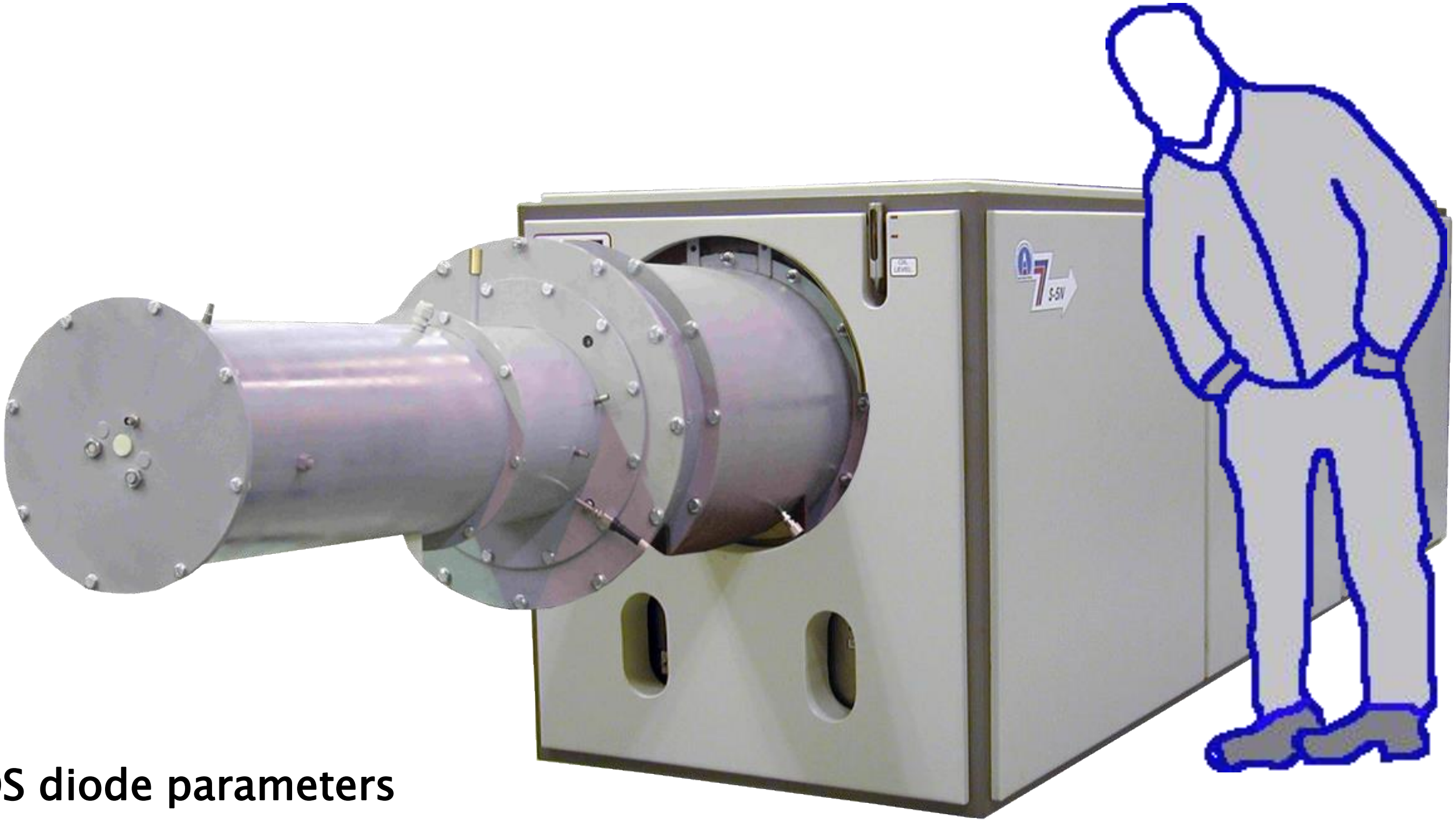


Output parameters S-5N generator

Pulse voltage	1 MV
Pulse current	3 kA
Pulse width	35-60 ns
PRF cont	300 Hz
PRF burst	500 Hz
Dimensions	3.5x1.4x1 m^3
Mass with oil	~ 2,500 kg

SOS generators of GW-range

IEP UB RAS



SOS diode parameters

Cutoff current	~14 kA
Cutoff time	~2 ns
Breaking power	~13 GW
$(dI/dt)_{max}$	~7 kA/ns

Output parameters of the S-500 generator

Loads	40–125 Ω
Peak voltage	500–900 kV
FWHM	~7 ns
Peak power	~6 GW
Burst PRF	up to 1 kHz

Proceedings of EPAC 2004, Lucerne, Switzerland

SOS-DIODE BASED PULSER FOR THE INJECTION SYSTEM OF THE COLLIDER VEPP-2000

B.I. Grishanov, F.V. Podgorny, A.S. Kasaev. BINP, Novosibirsk, RUSSIA

Abstract

We describe a high voltage pulser for supplying of kickers of the collider VEPP-2000 injection system. The

preliminary charged forming line to the load. Thyratrons or spark-gap switches are used in this scheme as the switch usually. There is a wide experience in development

Pulser's specifications

Output pulse amplitude	30-50 kV
Rise/fall time	≤ 30 ns
Flat-top duration	≥ 15 ns
Flap-top nonuniformity	< 10 %
Pulse amplitude instability	< 0.5 %
Jitter	< 1 ns
Load	50 Ohm
Repetition rate	≤ 2 Hz

SOS generators for KICKER systems

IEP UB RAS

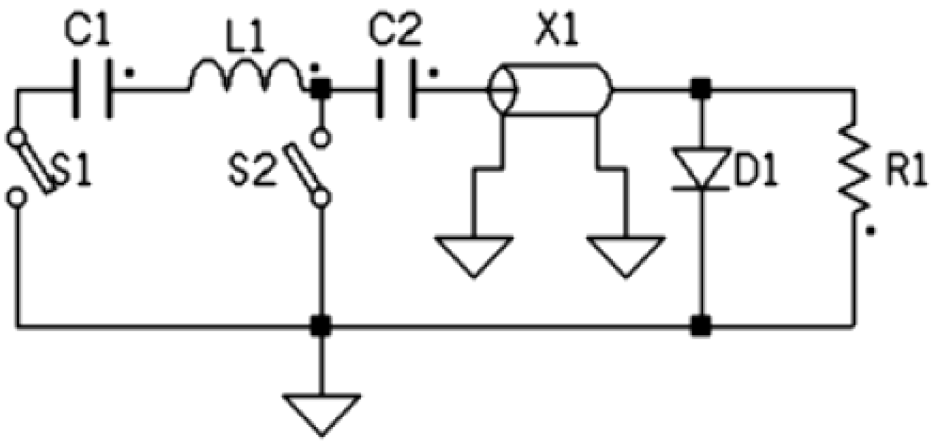


Fig. 4. Two-circuit scheme with pulse forming line.

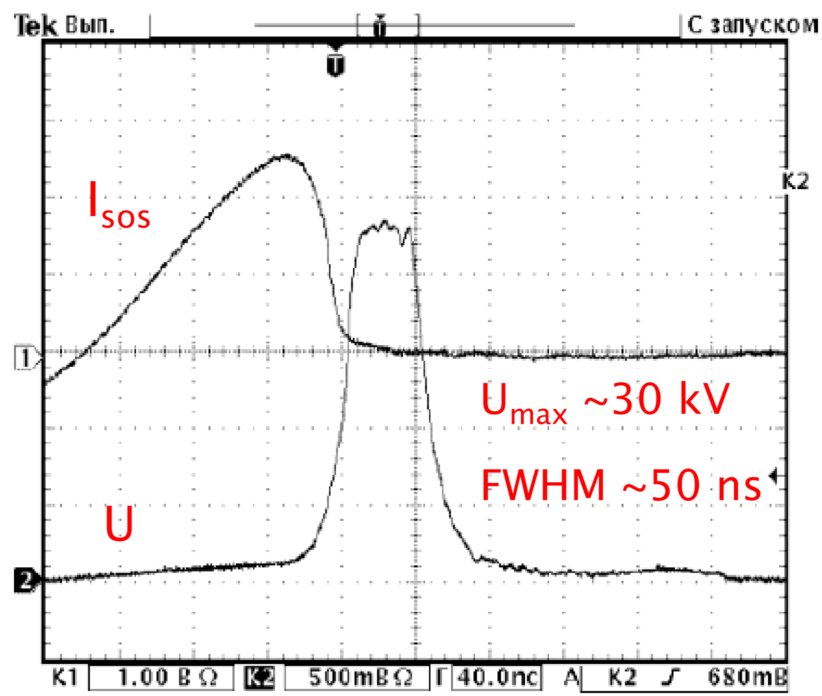
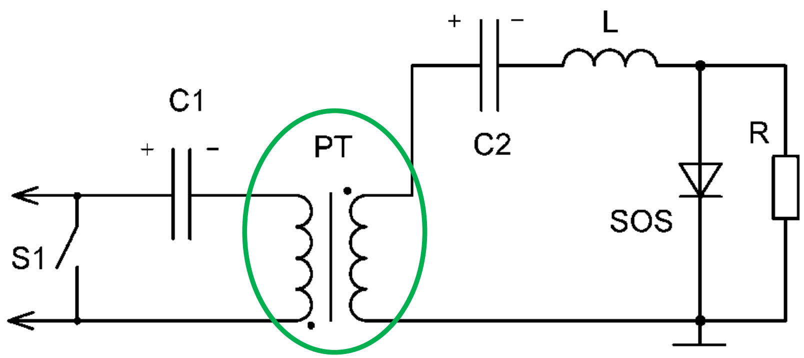
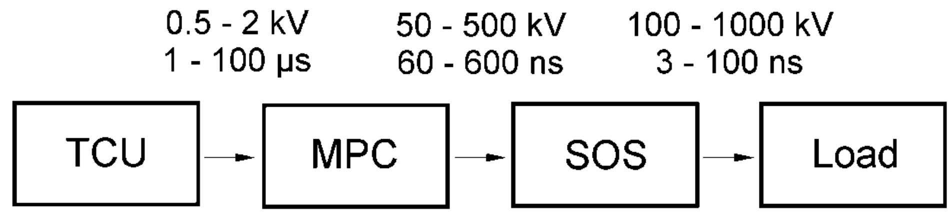


Fig. 5. The load pulse oscillograms.

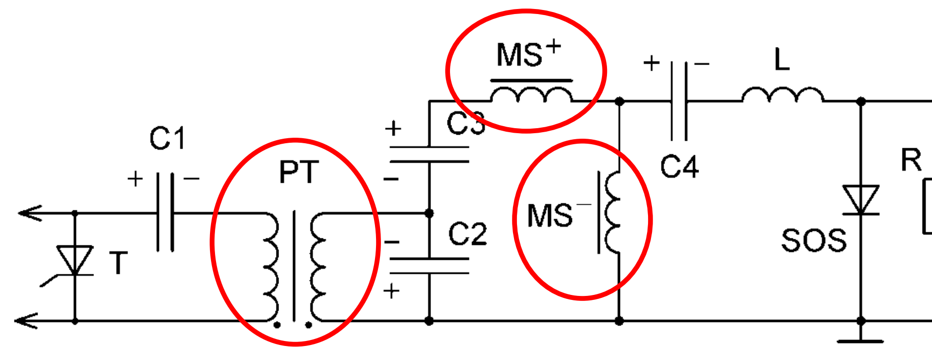
B.I. Grishanov, F.V. Podgorny, A.S. Kasaev, SOS-DIODE BASED PULSER FOR THE INJECTION SYSTEM OF THE COLLIDER VEPP-2000, Proceedings of EPAC 2004, Lucerne, Switzerland

SOS generator challenge

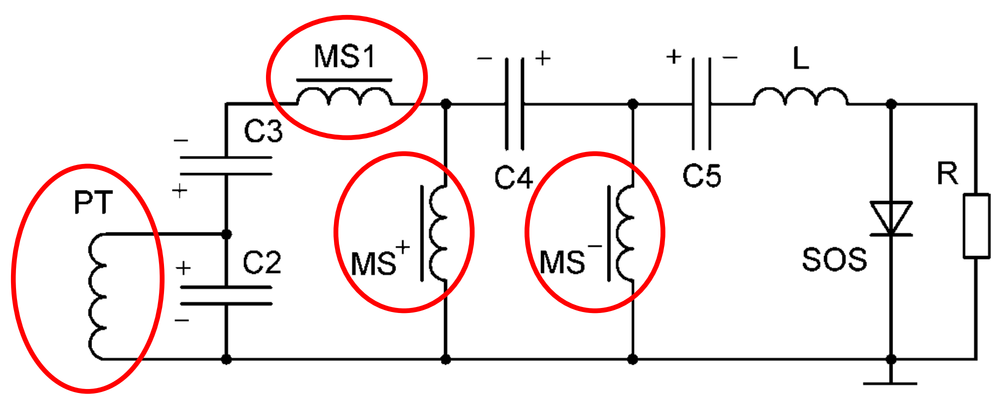




Block diagram of all-solid-state SOS based generators.



Electric circuit diagram at pulse energy ~ 1 – 10 J.



Electric circuit diagram at pulse energy ~ 10 – 100 J.

Target: SOS pumping through a single magnetic element: increasing the efficiency from 0.4–0.6 to 0.80–0.85

Main problem: Superfast high power solid-state primary switch S1 must be developed

Example:

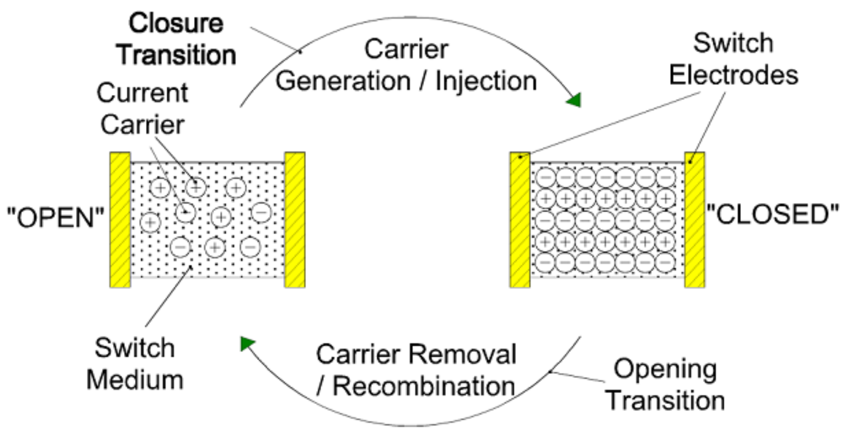
W = 100 J, t = 400 ns, U1 = 20 kV

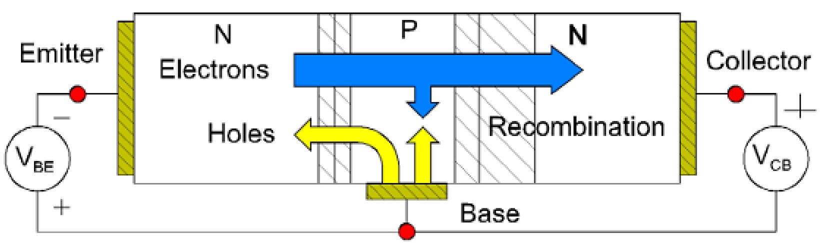
Peak current	40 kA
Current rise rate	300 kA/μs

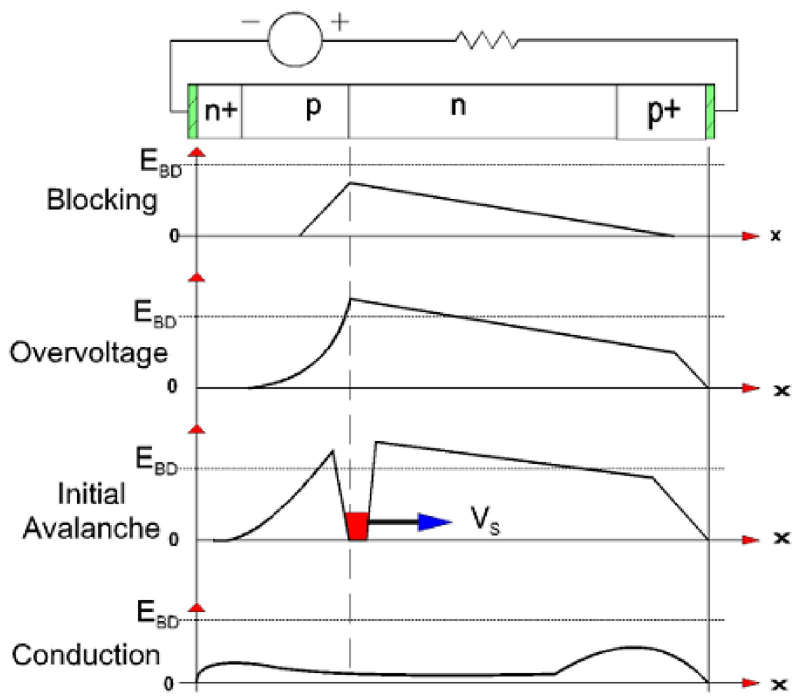
Semiconductor switches

IEP UB RAS

Carrier injection and impact-ionization switching mode in semiconductor switches.





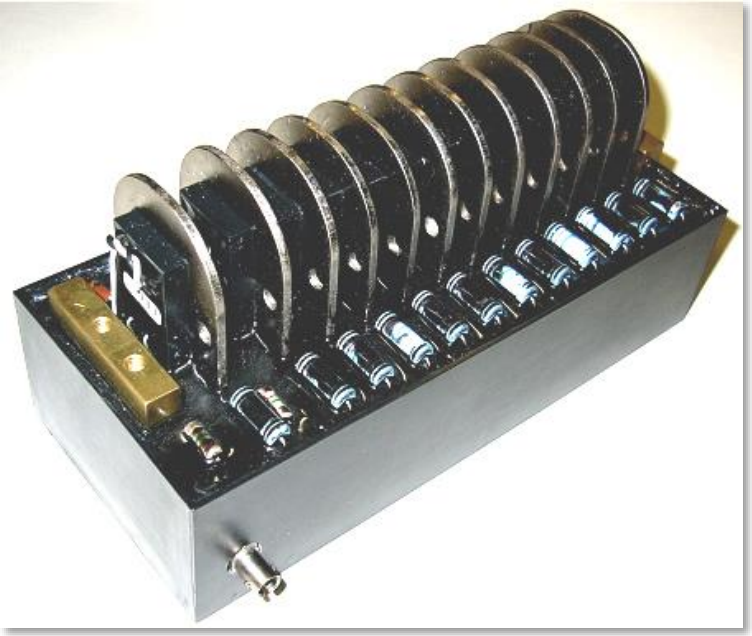


William Nunnally, A New Approach for Implementing HV (10 kV's) Fast Closure (ns) Semiconductor Switches.
In Proc. of 2014 Power Modulator and High Voltage Conference (IPMHVC), 2014 IEEE International , USA, Santa Fe, NM, pp.17-22

Semiconductor switches

IEP UB RAS

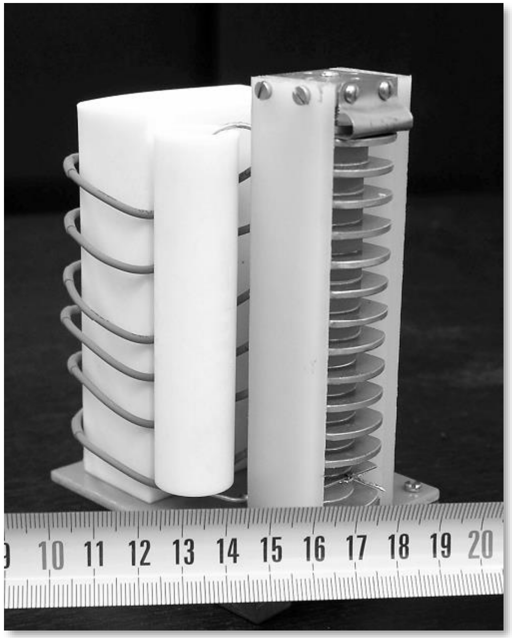
Carrier injection



Integral thyristors, model S33A
(Applied Pulsed Power, Inc)

U	48 kV
I	9 kA
dI/dt	40 kA/μs

Impact-ionization wave



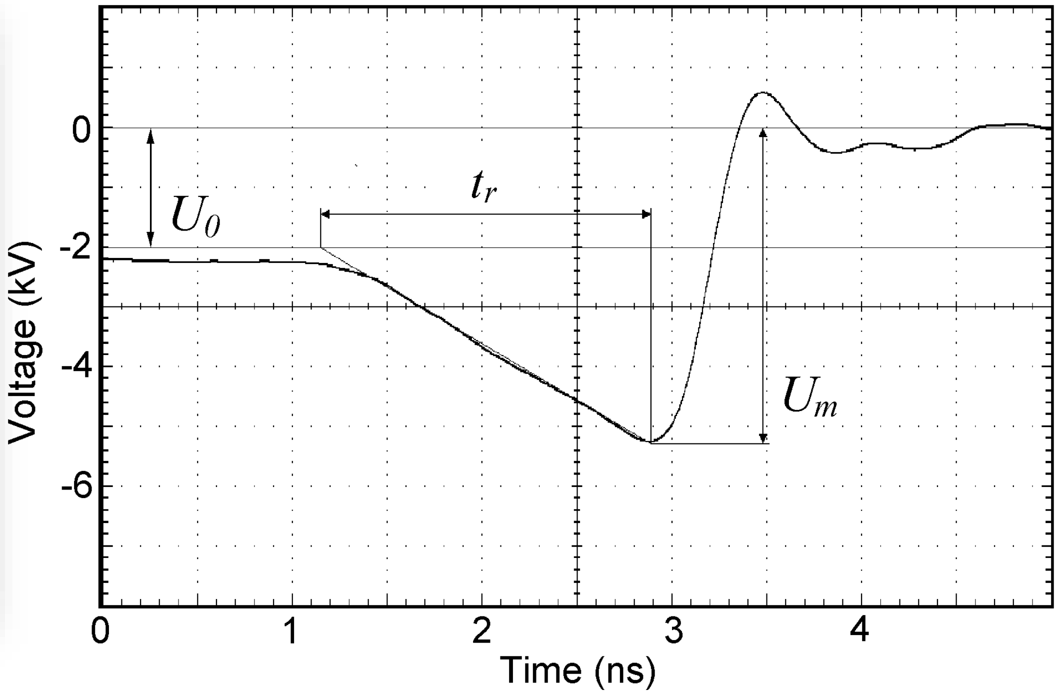
Fast-Ionization Dynistors FID
(Ioffe Institute, Saint Petersburg)

U	12-25 kV
I	1-5 kA
dI/dt	100-200 kA/μs

Thyristor triggered in impact-ionization wave mode

IEP UB RAS

Low-frequency commercial thyristor T343-500-20 (wafer diameter – 40 mm)

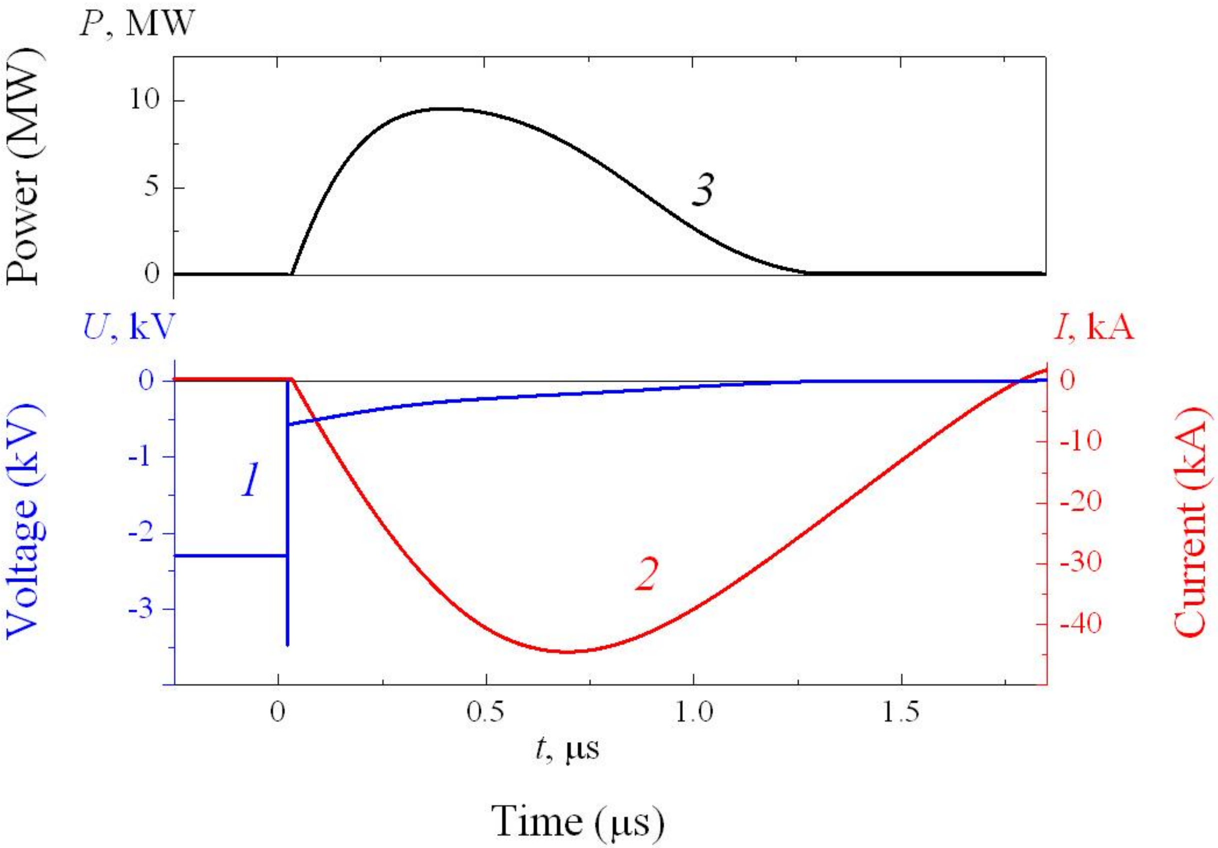


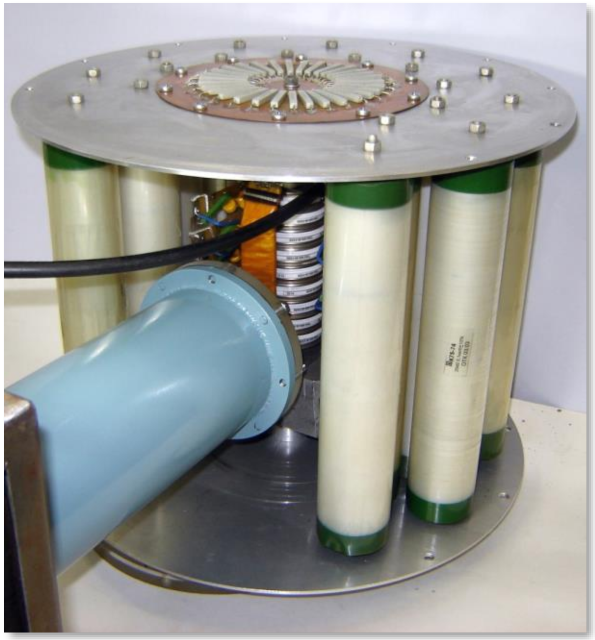
Operating voltage	2 kV
Surge current	8 kA
Current rise rate	400 A/μs

dU/dt	>1 kV/ns
Rise time	1–2 ns
Max voltage	5–6 kV
Switching time	200–400 ps

Submicrosecond range

Thyristors T343-500-20 40 mm wafer (9 in series)



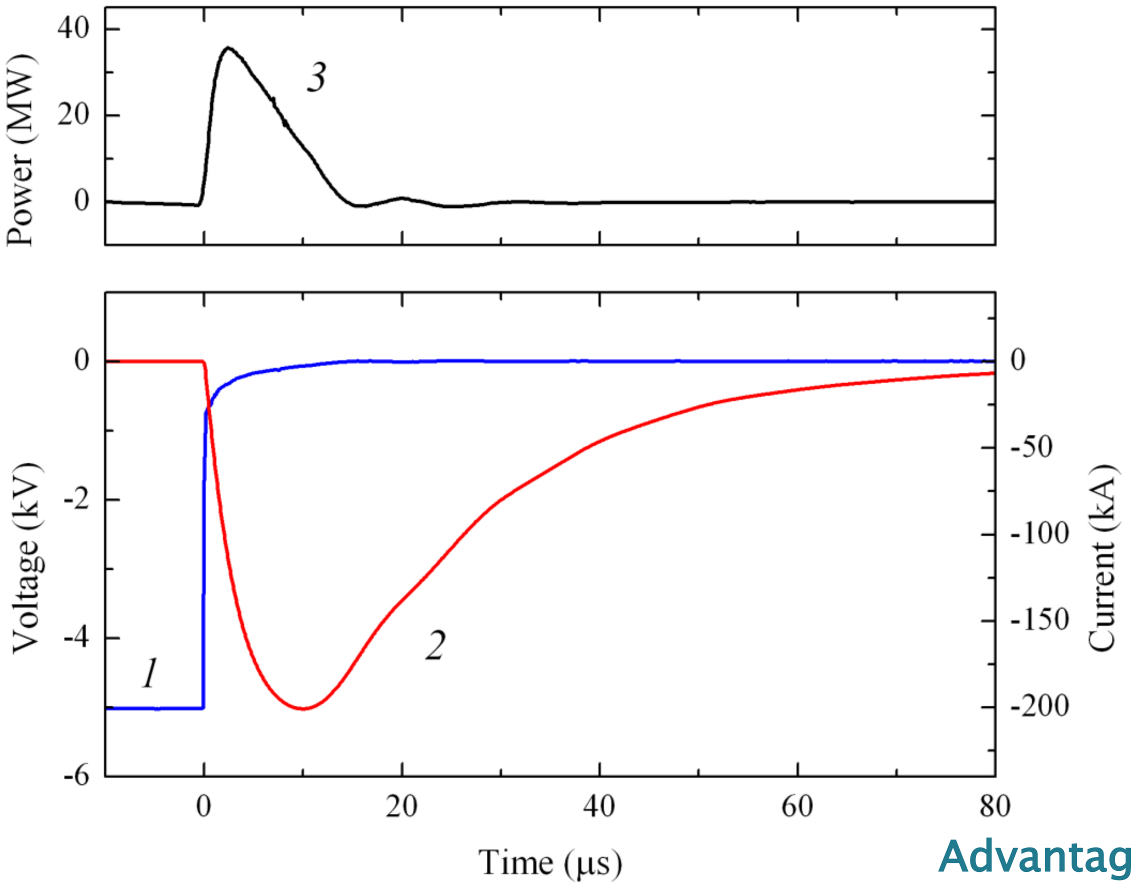


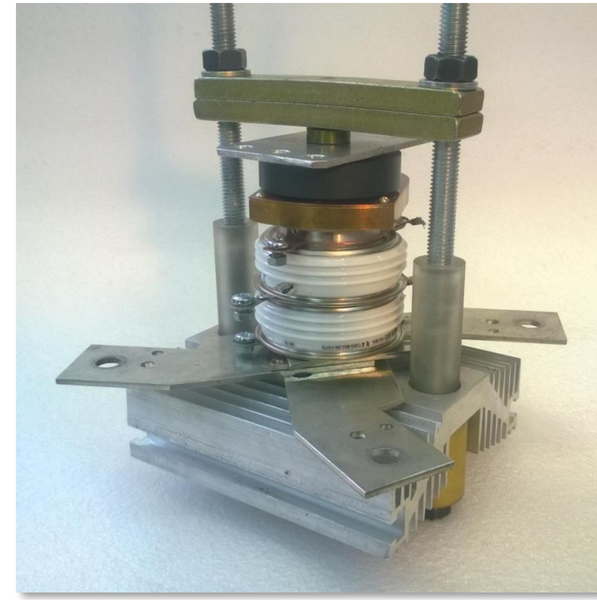
Voltage	20 kV
Resistive load	0.17 Ω
Peak current	45 kA
Current rise time	400 ns
Peak power	340 MW
Current rise rate	134 kA/µs
FWHM	~1 µs
Efficiency	0.85

Current rise rate is increased ~ 330 times in comparison with critical dI/dt value at usual triggering mode when a current pulse is applied to the gate electrode (0.4 kA/µs)

Microsecond range switch

Thyristors T253-800-24 56 mm wafer (2 in series)





Voltage	5 kV
Stored energy	12 kJ
Resistive load	18 mΩ
Peak current	200 kA
Peak power	720 MW
Current rise rate	58 kA/µs
FWHM	25 µs
Efficiency	0.97

Advantage of the switches:

Easy of access (electronic shop)

Low price (50-100 $ for 32-56 mm thyristor)

Disadvantage:

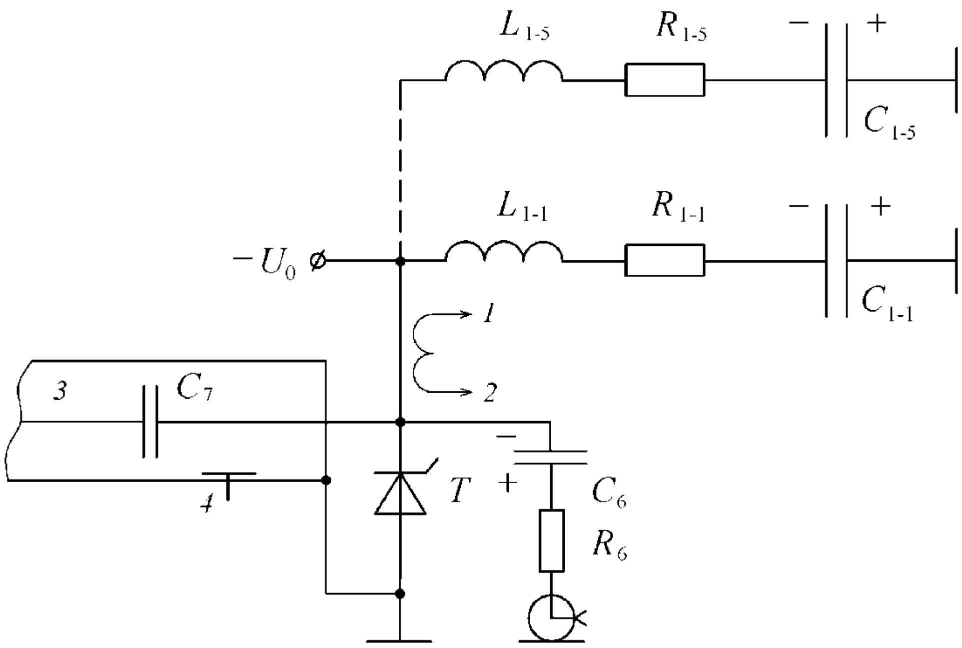
Fast triggering generator is needed

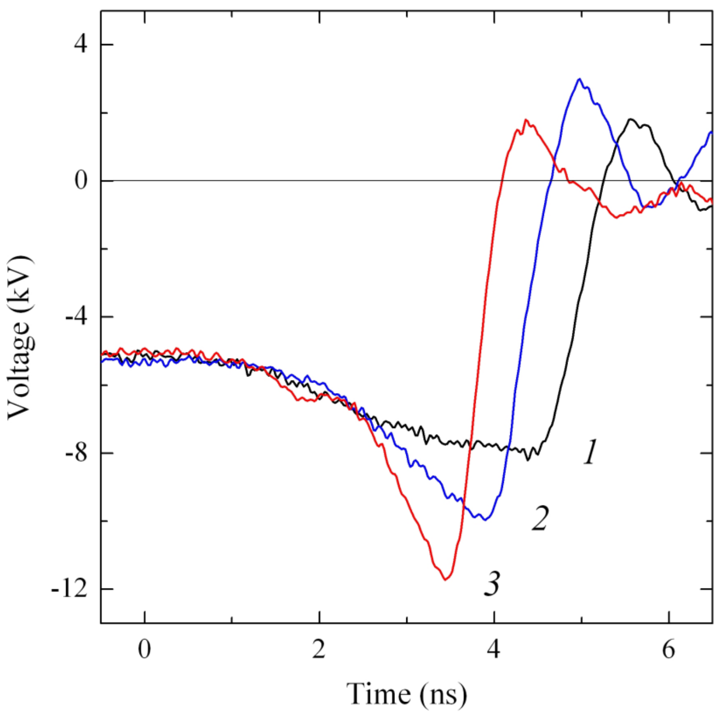
(1-2 kA, 5-10 kV, 3-6 ns FWHM)

dU/dt Factor

IEP UB RAS

Circuit diagram of the experimental setup.





Thyristors T453-500-24
56 mm wafer (2 in series)

Waveforms of the voltage across thyristors during switching process: *dU/dt* is ~0.5 (1), ~1.3 (*2*), and ~3.0 kV/ns (*3*).

dU/dt Factor

IEP UB RAS

Visual appearance of T253-800 thyristor's silicon wafer of 56 mm in diameter after breakdown with triggering pulse. Peak current is 262 kA, stored energy is about 15 kJ.

Visual appearance of T253-800 thyristor's silicon wafer of 56 mm in diameter after self-breakdown without triggering pulse. Peak current is 150 kA, stored energy is about 7 kJ.

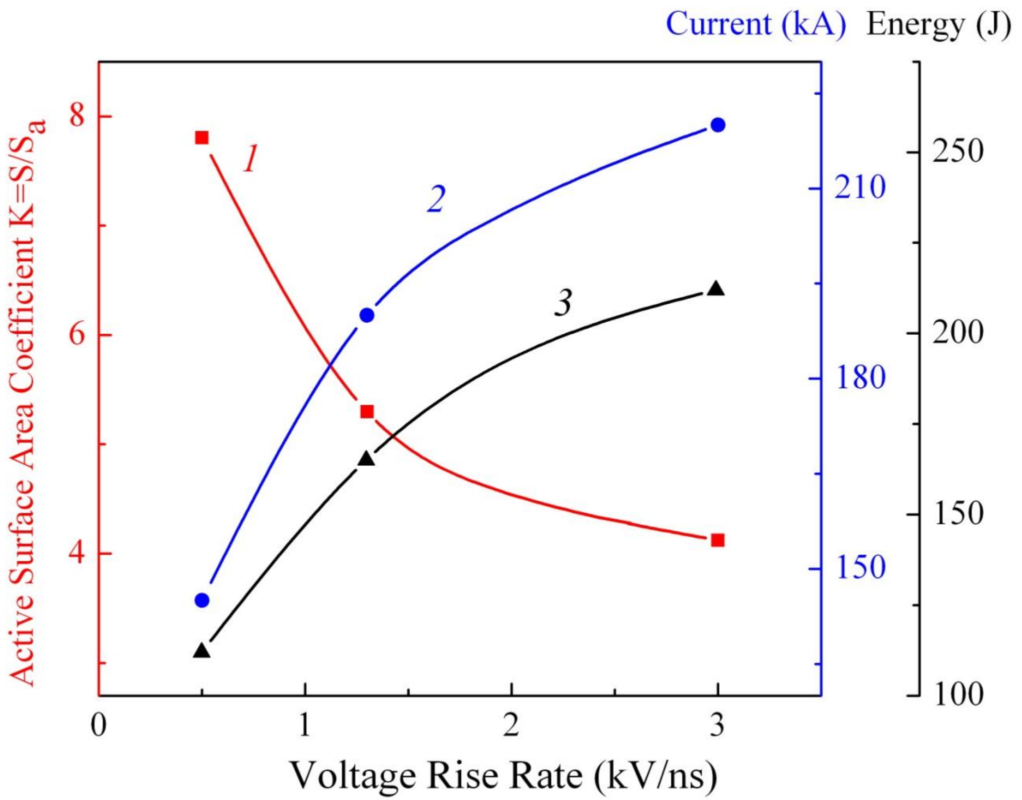
dU/dt Factor

IEP UB RAS

$$T_{cr} \approx 500°C$$

$$K = \frac{S}{S_a} = \frac{T_{cr} - T_0}{\Delta T}$$

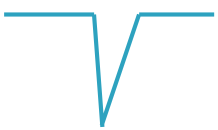
dU/dt, kV/ns	0.5	1.3	3.0
I_{br}, kA	145	190	220
W_T, J	112	165	212
ΔT, ^{0}C	61	90	115
$K = S/S_a$	7.8	5.3	4.1
1/K x 100%	12.8	18.9	24.4

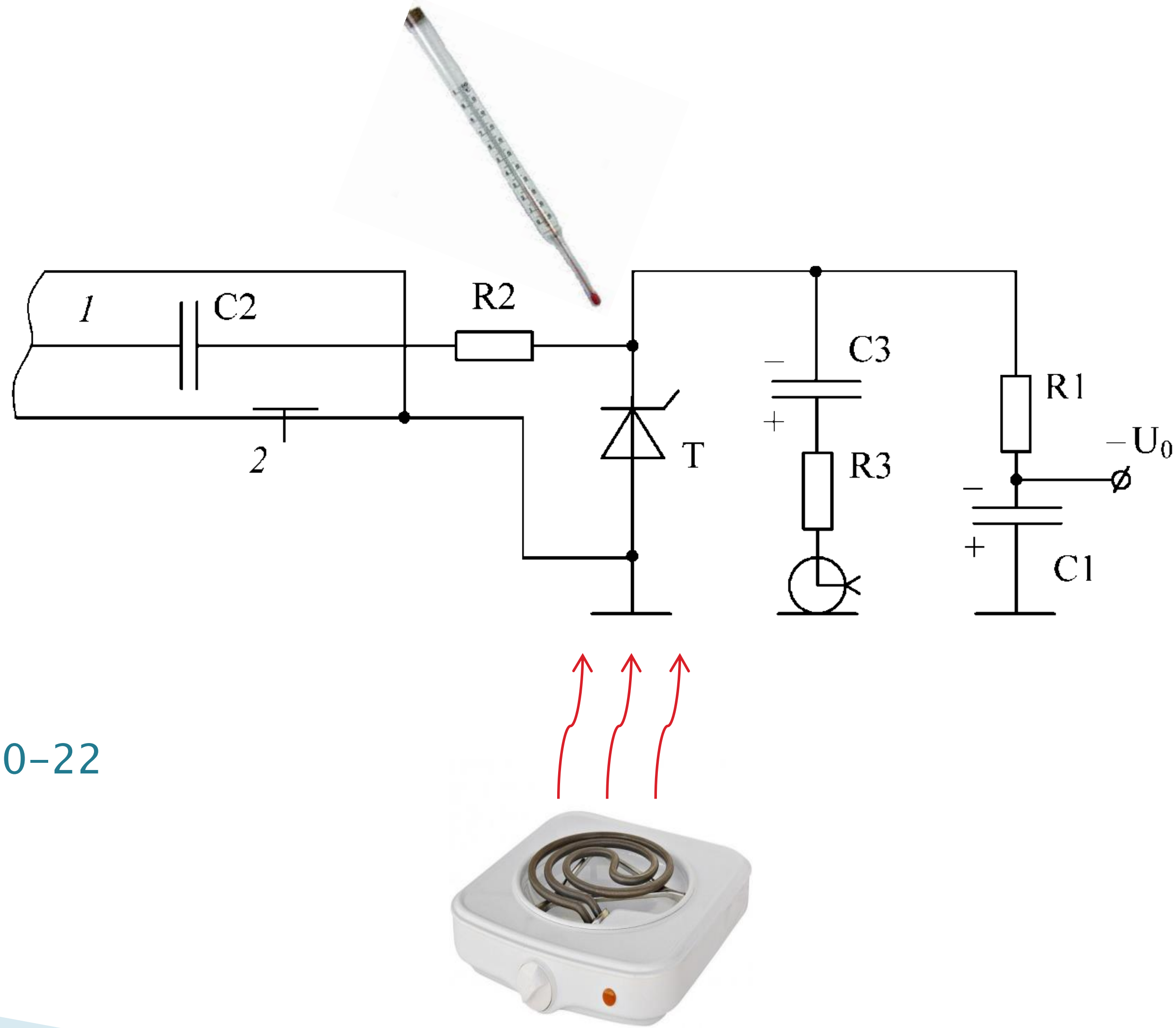


Coefficient of the structure active surface area K = S/Sa (curve *1*), amplitude of the failure current (curve *2*) and thyristor dissipated energy (curve *3*) as a function of the voltage rise rate at the triggering stage.

Effect of dU/dt and Temperature on Thyristor Switching Process

IEP UB RAS





U~45 kV
R = 50 Ω
$t_{0.1-0.9}$ = 0.8 ns

Thyristor T323-320-22
32 mm wafer

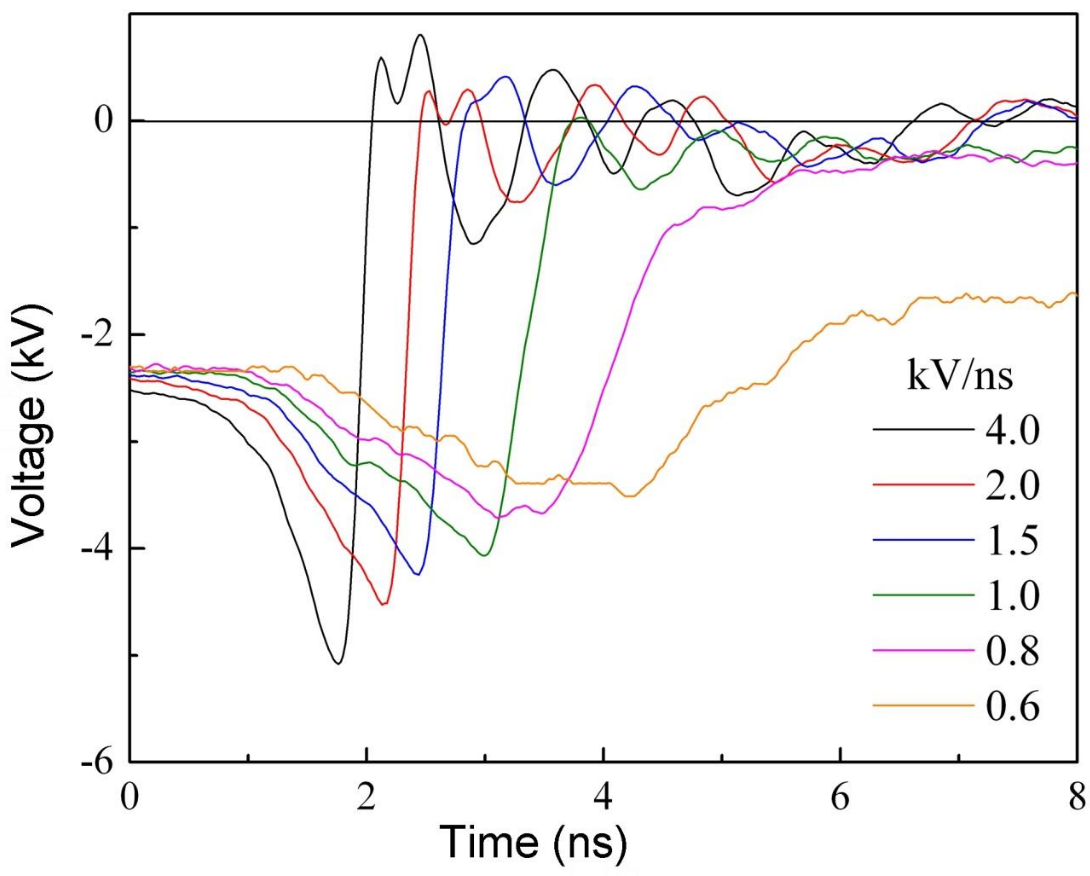
Effect of dU/dt and Temperature on Thyristor Switching Process

IEP UB RAS

T=25°C=const

dU/dt=0.6–4.0 kV/ns

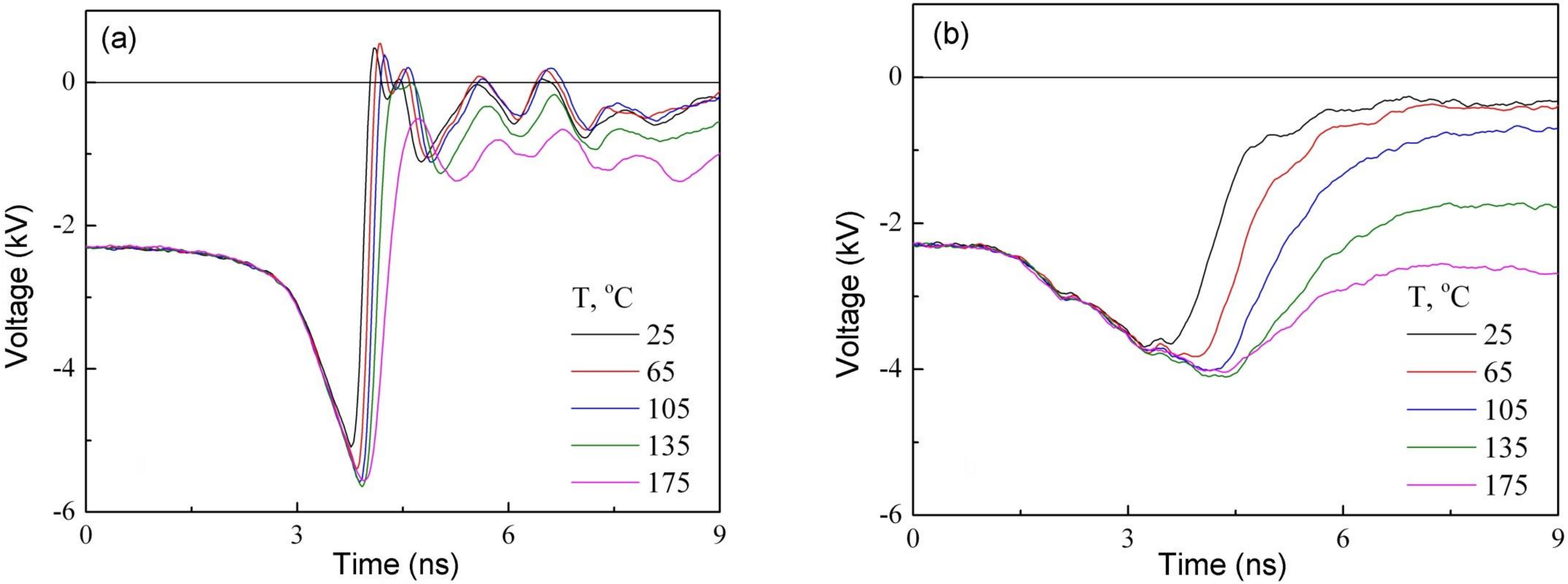
Waveforms of the voltage across the thyristor during switching process at room temperature (T = 25 °C) and different values of the voltage rise rate *dU/dt*.



Effect of dU/dt and Temperature on Thyristor Switching Process

IEP UB RAS

dU/dt = 4.0 kV/ns　　　　dU/dt = 0.8 kV/ns

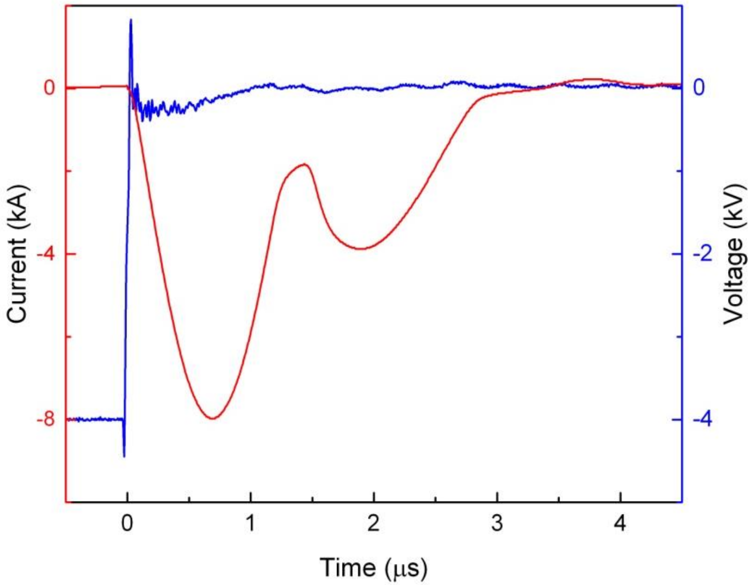


Waveforms of the voltage across the thyristor during switching process at different temperatures: *dU/dt* = 4 kV/ns (a) and 0.8 kV/ns (b).

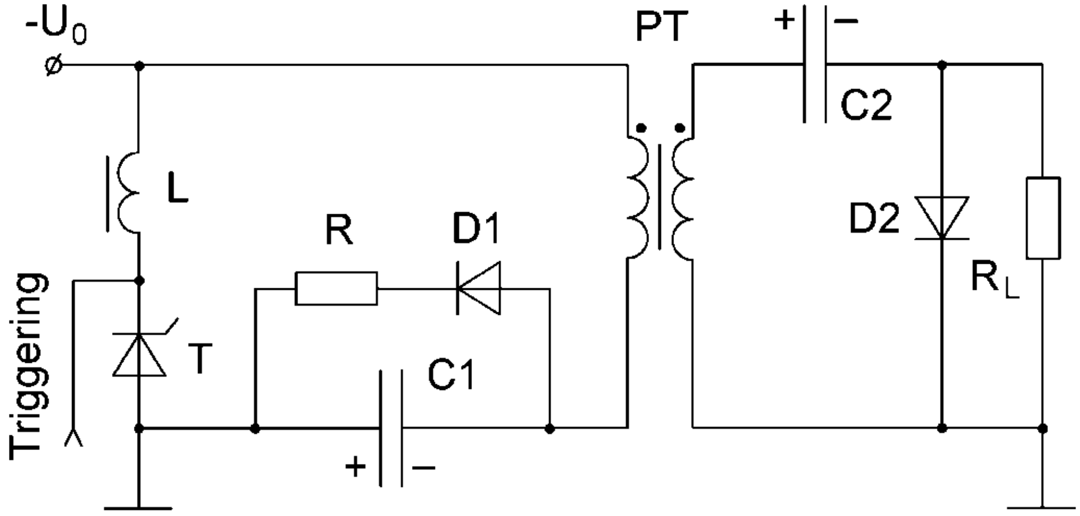
Repetitive Mode of Operation

IEP UB RAS

Thyristors T453-500-24 40 mm wafer (2 series connected).



Waveforms of the voltage and current for the thyristor switch during its operation in repetitive mode.



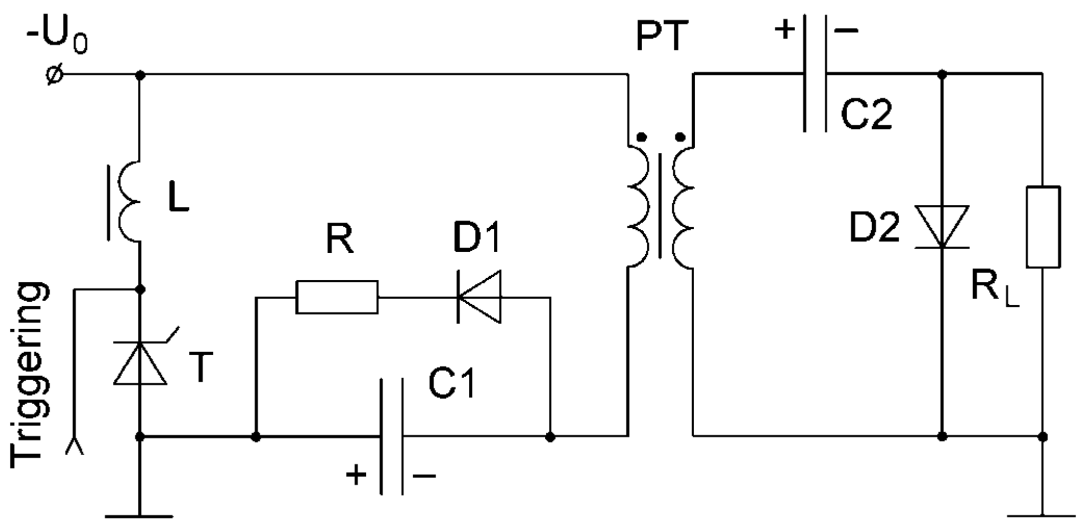
Circuit diagram of the experimental setup for repetitive mode of operation.

Repetitive Mode of Operation

IEP UB RAS

Thyristors T453-500-24 40 mm wafer (2 series connected).

Primary switch parameters	
Charging voltage	U = 4.0 kV
Maximum current	I_{max} = 8 kA
Maximum current rise rate	dI/dt = 18 kA/μs
Pulse duration (FWHM)	t_{FWHM} = 1.4 μs
Stored Energy	W_0 = 16 J
Energy dissipated in the thyristors	W ≈ 1 J
Efficiency	94 %



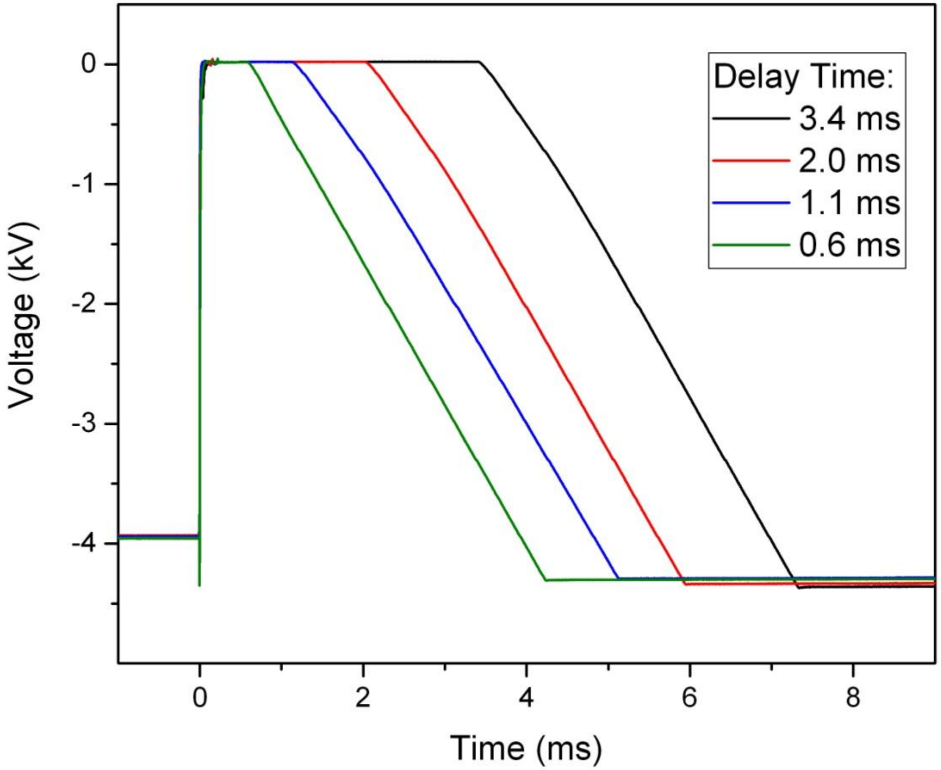
Circuit diagram of the experimental setup for repetitive mode of operation.

Repetitive Mode of Operation

IEP UB RAS

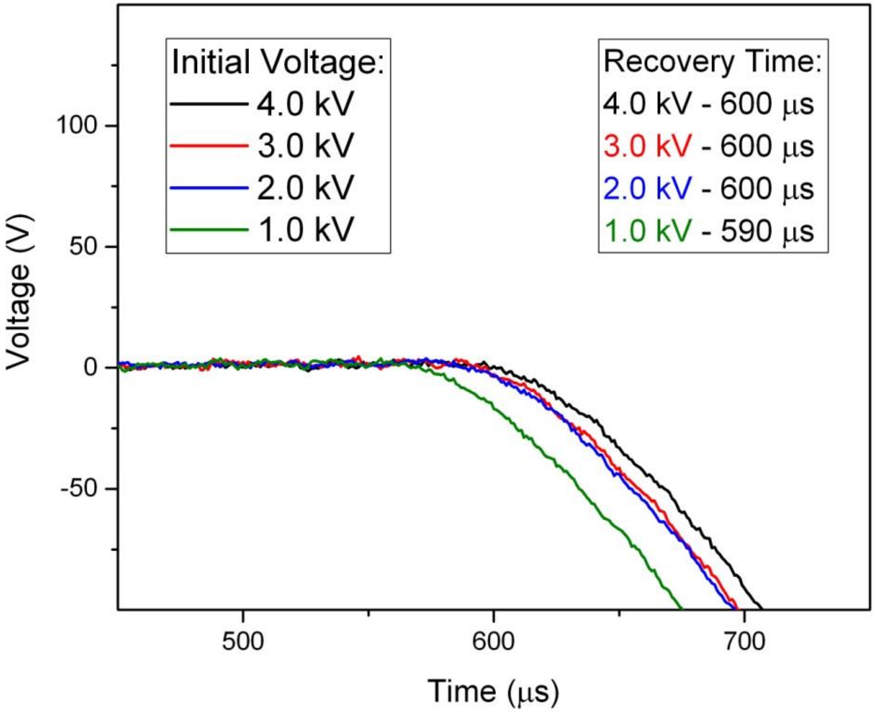
Thyristor recovery time

Waveforms of the voltage across the thyristor switch during the thyristor recovery time analysis.

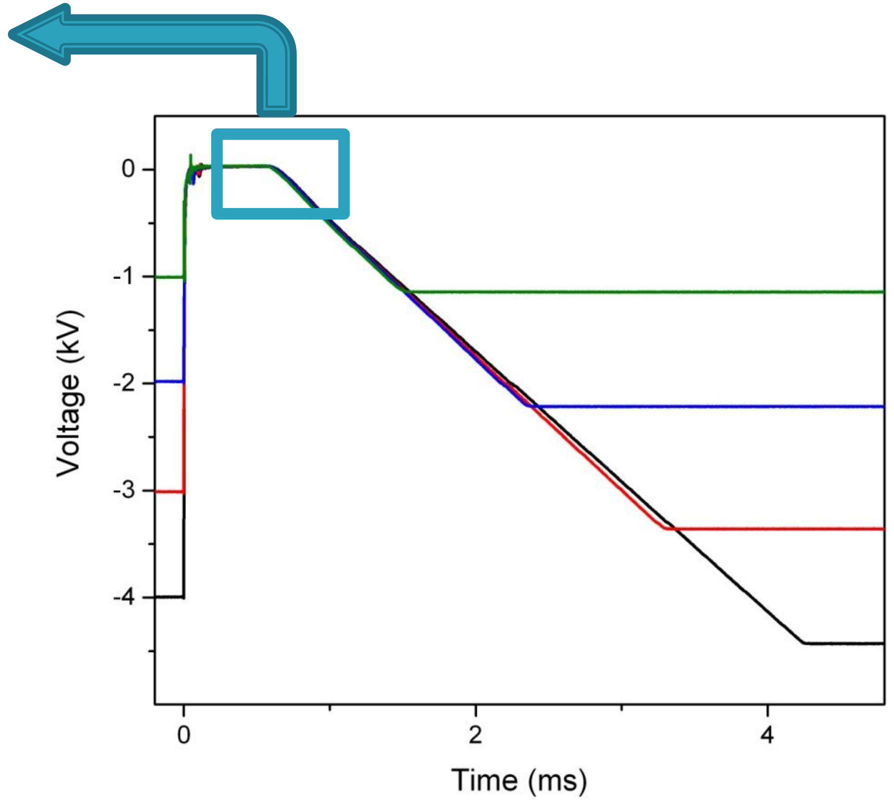


Repetitive Mode of Operation

IEP UB RAS



Thyristor recovery time at the different initial voltage.



Waveforms of the voltage across the thyristor switch at the different initial voltage.

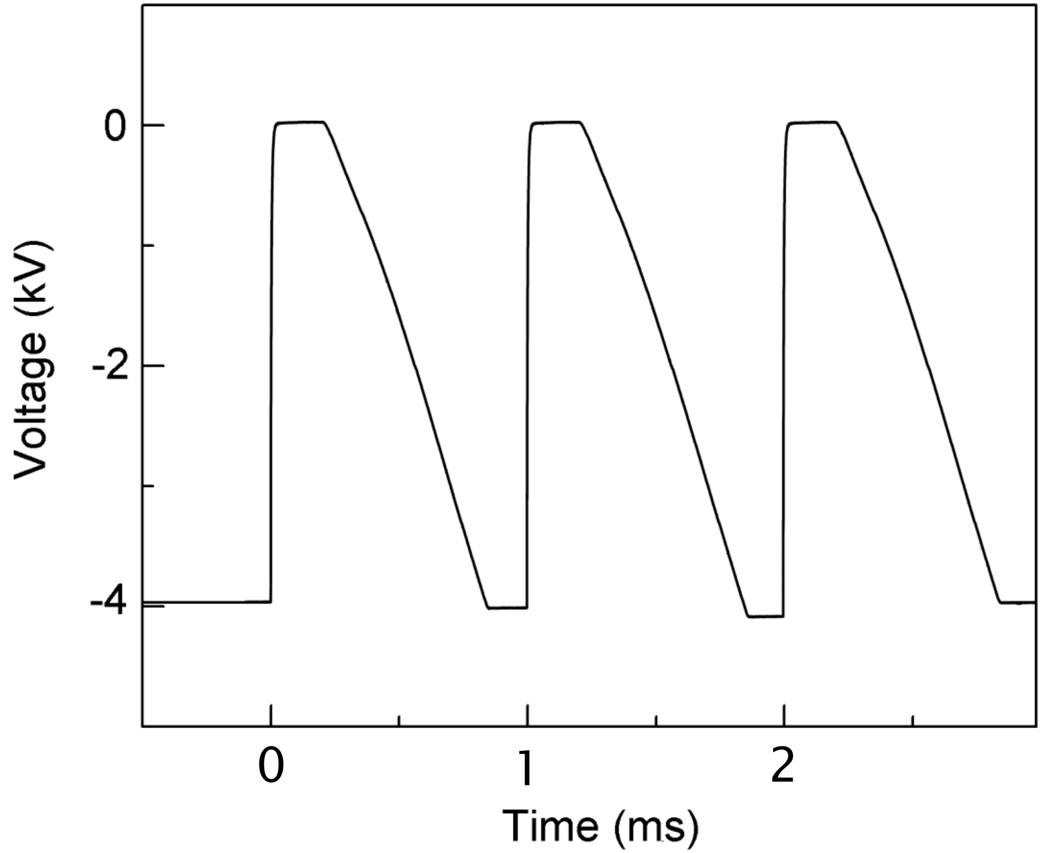
Repetitive Mode of Operation

IEP UB RAS

Burst mode1000 Hz
a few seconds.

Over 10^{6} pulses were performed.

No thyristor degradation was observed.



Waveform of the voltage across the thyristor switch at PRF of 1000 Hz.

Conclusion and Future Works

IEP UB RAS

The following results were achieved: submicrosecond range switch – 20 kV, 45 kA, 134kA/μs; microsecond range switch – 5 kV, 200 kA, 58 kA/μs.

Two main factors effect on the switching process. This is the voltage rise rate dU/dt at the triggering stage and temperature of the semiconductor wafer.

Thyristor-based switches were successfully tested in repetitive mode. These switches are used in real pulsed power applications.

Temperature and dU/dt effects need to be investigated more detailed including numerical simulations, which will give better understanding of the switching mechanism at impact-ionization wave mode.

The study was supported by Russian Foundation for Basic Research (RFBR), research projects number 15-08-07821 and 17-08-00406

IEP UB RAS

Russian Academy of Sciences
Institute of Electrophysics
Pulsed Power Laboratory

Thank you for your attention!

HIGH CURRENT AND CURRENT RISE RATE THYRISTOR BASED SWITCHES

Anton Gusev, S. Lyubutin, A. Ponomarev, S. Rukin,

B. Slovikovsky, S. Tsyranov

PULse POwer for Kicker Systems (PULPOKS) workshop 2018